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Fragipan Soils in the Lower Mississippi River Valley

Their Distribution, Characteristics, Erodibility, Productivity, and Management

ABSTRACT

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This publication discusses fragipan soils formed in the loess uplands of the lower Mississippi River Valley. A series of studies was conducted to determine the effects of erosion on the properties and productivity of a fragipan soil. Soil samples were collected at five sites and analyzed. Twelve experimental field plots of soybean [Glycine max. (L.) Merr.] were installed at three sites. Results from the studies indicated that erodibility increased between the uneroded and slightly eroded phases and then decreased at the moderate and severely eroded phases. Average soybean grain yields were 2,417, 1,953, and 1,877 kg ha^{-1} at the slightly, moderately, and severely eroded sites, respectively. A yield-depth-to-fragipan curve derived from these data showed that the greatest grain yield reduction per increment of soil loss occurred as soil depth decreased from 60 to 50 cm. This indicates that management systems should be designed to preserve a minimum thickness of approximately 60 cm above the fragipan to maintain the productivity of these soils.

Keywords: fragipan horizon, fragipan soil, loess soils, Mississippi River Valley, and soil erodibility.

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Fragipan Soils in the Lower Mississippi River Valley: Their Distribution, Characteristics, Erodibility, Productivity, and Management

F.E. Rhoton, D.D. Tyler, and D.L. Lindbo

The loess uplands of the lower Mississippi River Valley include several million ha of soils that contain fragipan horizons. These soils, which are important to the agricultural economy of the region, are highly susceptible to erosion losses due to unstable aggregates, a sloping landscape, and abundant rainfall, much of which occurs as intense thunderstorms. Fragipan horizons restrict root growth to the extent that continued erosion systematically reduces soil-water storage capacity and productivity, unless ample rainfall occurs throughout the growing season. Once soil thickness above the fragipan decreases so that row-cropping is uneconomical in years with average rainfall, productivity cannot be restored by standard reclamation methods. Management systems that maintain or improve productivity must be developed, or extensive areas will eventually go permanently out of production.

Several recent research projects have dealt with erodibility, the effect of erosion on productivity, and management practices on these soils. This research has provided basic information from which more detailed, comprehensive projects can be designed that target fragipan soils and their response to erosion. This report summarizes the latest findings and suggests research needed to maintain this regionally important soil resource in a productive state.

Identification and Distribution of Fragipan Soils

Soils containing fragipan horizons in the lower Mississippi River Valley are most prevalent in the loess deposits of Major Land Resource Area (MLRA) 134, the Southern Mississippi Valley Silty Uplands (U.S. Department of Agriculture 1981). This area comprises approximately 51,410 km^2 (19,850 mi^2) that extend in a continuous zone east of the Mississippi River from its juncture with the Ohio River into the northern parishes of southeastern Louisiana (fig. 1). Other areas in this MLRA exist west of the Mississippi River, principally at Crowley's Ridge in Arkansas and Sicily Island in Louisiana.

In MLRA 134, significant areas of the fragipan soils are restricted to Mississippi and Arkansas, which make up about 80 percent of the total. The remainder exists in Tennessee and Louisiana. Estimated areas of fragipan soils formed in all types of parent materials in these states approach 4.3 Mha, but this figure will probably double when all soil surveys are completed (Hudnall and Williams 1989).

Identification of fragipan horizons is based on a set of field criteria that include brittleness, tendency to slake in water, evidence of pedogenesis, presence of prisms arranged in a horizontal plane separated by vertical streaks, and high bulk density compared with that of overlying horizons (Witty and Knox 1989). Most of these criteria apply to fragipan horizons worldwide. However, the high bulk density requirement is not a useful criterion for identifying fragipans in the lower Mississippi River Valley where some overlying horizons are denser (Lindbo et al. 1994).

The loess parent material in which the fragipan soils of MLRA 134 formed originated as sediment from glacial outwash deposited in the floodplain of the lower Mississippi River Valley. This material was eventually blown east by prevailing winds and was redeposited between 9,000 and 20,000 yr ago (Pye and Johnson 1988). The loess stratigraphic unit (termed Peoria), which makes up the present-day surface, decreases logarithmically in thickness with distance from the source (Snowden and Priddy 1968). It ranges from 4.6 to 21.3 m thick along the bluff of the Mississippi River to 0 within an east to west distance of less than 161 km (Wascher et al. 1947). Fragipan horizons within 16 km of the bluff are generally uncommon on this landscape. The predominant soil series containing the fragipan horizons are Loring and Grenada, and to a lesser extent, Calloway and Henry on wetter sites.

Characteristics of Fragipan Soils

The characteristics of fragipan soils can vary depending on slope position and the extent of erosion. An early account of these loess soils in an uneroded state indicated a surface horizon thickness of 25 to 30 cm (Hilgard 1880). The subsoil (probably a fragipan horizon) was described as existing 60-90 cm below the surface. Today, the few existing uneroded tracts of fragipan soils serve as valuable source areas for determining more precisely what soil properties were like before cultivation and erosion.

The properties of three uneroded fragipan soils in Mississippi and Kentucky have been reported by Seatz (1959). In these Grenada profiles, the thickness of the surface horizons ranged from 15 to 25 cm, and organic matter content ranged from 3.5 to 6.8 percent. Surface textures were either silt loam or silt, with silt content ranging from 78 to 88 percent. Clay content in this zone averaged about 12 percent. The pH ranged from 5.2 to 6.4 and depth to fragipan horizons was 64-76 cm. An uneroded Grenada soil sampled in west Tennessee had similar characteristics to those previously mentioned, with a 20-cm-thick A horizon, 5 percent organic matter, 82 percent silt, 17 percent clay, and a depth to fragipan of about 76 cm (Rhoton and Tyler 1990). Assuming that Hilgard (1880) described a fragipan soil, these data for uneroded fragipan soil properties appear to be similar to precultivation conditions.

Once these soils were cleared and exposed to cultivation with its associated erosion, their properties changed dra-

matically. Rhoton and Tyler (1990) compared the characteristics of four fragipan pedons in Tennessee and Mississippi that were eroded to different depths, using the relative depth to fragipan horizon to assign erosion classes (fig. 2). The profile descriptions for these soils are described below.

Uneroded Site, Crockett Co., TN (fig. 2a)

Horizon	Description
01	8 to 2 cm: partially decomposed leaves and twigs from mixed hardwood trees.
02	2 to 0 cm: decomposing leaves and twigs.
A1	0 to 10 cm: very dark grayish-brown (10YR 3/2) silt loam; weak, very fine granular structure; very friable; many fine and medium roots; few coarse roots; gradual, wavy boundary.
A2	10 to 20 cm: dark brown (10YR 3/3) silt loam; weak, fine granular structure; friable; common, fine, and medium roots, few coarse roots; common, coarse root channels; gradual, wavy boundary.
BA	20 to 36 cm: dark yellowish-brown (10YR 4/4) silt loam; weak, medium, subangular blocky structure; friable; few, fine, very dark grayish-brown (10YR 3/2) Fe-Mn nodules and stains; common, medium, and coarse root channels filled with silt that is lighter in color than matrix; common, fine, and medium roots; gradual, smooth boundary.
Bw	36 to 48 cm: dark yellowish-brown (10YR 5/6) silt loam; moderate, medium, subangular blocky structure; friable; common, fine, very dark grayish-brown (10YR 3/2) Fe-Mn nodules and stains; common, medium, and coarse root channels filled with silt; common, fine, and medium roots; gradual, smooth boundary.
Bt	48 to 64 cm: yellowish-brown (10YR 5/6) silt loam; moderate, medium, angular to subangular blocky structure; friable; common, fine, and medium very dark grayish-brown (10YR 3/2) Fe-Mn nodules and stains; thin, patchy clay films lining root channels; common, medium, faint pale brown (10YR 6/3) mottles; common, medium, and fine roots; gradual, smooth boundary.
E/Btx	64 to 74 cm: light brownish-gray (10YR 6/2) silt loam matrix; massive, friable; common, dark brown (7.5YR 4/4) brittle peds dispersed throughout the matrix; common, medium, faint pale brown (10YR 6/3) mottles; common, fine, distinct, very dark gray (10YR 3/1) Mn stains; few, fine, and medium roots; abrupt, irregular boundary.
Btx1	74 to 127 cm: dark brown (7.5YR 4/4) silt loam; gray (10YR 6/1) coatings 10 to 40 mm thick on faces of polygonal structure units; common, medium, distinct, light brownish-gray (10YR 6/2) mottles; common, fine, distinct, very dark gray (10YR 3/1) Mn stains; moderate, medium, subangular and angular structure; very firm and brittle; gradual, wavy boundary.
Btx2	127 cm+: dark brown (7.5YR 4/4) silt loam; gray (10YR 6/1) coatings 5 to 25 mm thick on faces of polygonal structural units; common, medium, distinct, yellowish-brown (10YR 5/6) Fe stains; common, fine, distinct, very dark gray (10YR 3/1) Fe-Mn stains; subangular to angular blocky structure; very firm and brittle.

Slightly Eroded Site, Holly Springs, MS (fig. 2b)

Horizon	Description
Ap	0 to 15 cm: dark yellowish-brown (10YR 4/4) silt loam; weak, fine, granular structure; common, fine roots; few to common, fine, very dark grayish-brown (10YR 3/2) Fe-Mn nodules and stains; abrupt, smooth boundary.
BA	15 to 28 cm: yellowish-brown (10YR 5/6) silt loam; moderate, medium, angular to subangular blocky structure; few, fine roots; few, fine, very dark grayish-brown (10YR 3/2) Fe-Mn nodules and stains; gradual, wavy boundary.
Bt1	28 to 43 cm: yellowish-brown (10YR 5/6) silt loam; moderate, medium, angular to subangular blocky structure; few, fine roots and root channels; few, fine, very dark grayish-brown (10YR 3/2) Fe-Mn nodules and stains; few, faint pale brown (10YR 6/3) silt coatings on ped faces; common, fine pores; gradual, wavy boundary.
Bt2	43 to 61 cm: yellowish-brown (10YR 5/4) matrix with yellowish-brown (10YR 5/6) inclusions dispersed throughout; silt loam; weak, fine to medium, angular to subangular blocky structure; few, fine, very dark grayish-brown (10YR 3/2) Fe-Mn nodules and stains; common, fine, and medium pores; common, distinct, light brownish-gray (10YR 6/2) silt coatings in pores and on ped faces; gradual, wavy boundary.
E/Bx	61 to 74 cm: light brownish-gray (10YR 6/2) silt loam; 5 percent dark brown (7.5YR 4/4) brittle peds; weak, fine to medium, subangular blocky structure; common, fine, and medium voids; abrupt, irregular boundary.

Btx1 — 74 to 88 cm: dark brown (7.5YR 4/4) silt loam; strong, coarse prisms breaking down to a firm, medium, angular blocky structure; light brownish-gray (10YR 6/2) silt coatings on prism faces; thick, continuous clay films (10YR 6/1) coating ped faces and lining channels; polygons ranging up to 20 cm wide; common, fine, distinct, very dark gray (10YR 3/1) Fe-Mn stains; gradual, wavy boundary.

Btx2 — 88 to 100 cm+: dark brown (7.5YR 4/4) silt loam; few, fine, distinct mottles (10YR 4/4) on polygon surfaces; common, fine to medium, very dark grayish-brown (10YR 3/2) Fe-Mn stains; polygons range from 7 to 25 cm wide and are separated by light brownish-gray (10YR 6/2) seams 2 to 7 cm wide; moderate, coarse prisms breaking down to moderate, medium, subangular blocky structure.

Moderately Eroded Site, Holly Springs, MS (fig. 2c)

Horizon	Description
Ap	0 to 11 cm: dark yellowish-brown (10YR 4/4) and yellowish-brown (10YR 5/4) silt loam; weak, fine granular structure; common, fine roots; few to common, fine and medium, very dark grayish-brown (10YR 3/2) Fe-Mn nodules and stains; few silt-coated peds as inclusions; abrupt, smooth boundary.
Bw1	11 to 23 cm: yellowish-brown (10YR 5/6) silt loam; weak, fine to medium, subangular blocky structure; few fine roots; few fine to medium, distinct, very dark grayish-brown (10YR 3/2) Fe-Mn nodules and stains; few dark brown (7.5YR 4/4) brittle peds dispersed throughout matrix; common, distinct pale brown (10YR 6/3) silt coatings; gradual, wavy boundary.
Bw2	23 to 37 cm: light yellowish-brown (10YR 6/4) silt loam matrix with common, fine to medium, strong brown (7.5YR 5/6) brittle peds dispersed throughout; few fine roots; common, fine, very dark grayish-brown (10YR 3/2) Fe-Mn stains associated with brittle peds; moderate, fine to medium, angular to subangular blocky structure; common, fine to medium pores; gradual, wavy boundary.
E/Bx	37 to 47 cm: pale brown (10YR 6/3) silt loam matrix with fine to medium, strong brown (7.5YR 5/6) brittle peds and medium to large, dark brown (7.5YR 4/4) brittle peds dispersed throughout matrix occupying 10 percent of the volume; matrix weak, fine granular structure; common, very dark grayish-brown (10YR 3/2) Fe-Mn stain associated with brittle peds; common, fine to medium pores; abrupt, irregular boundary.
Btx1	47 to 75 cm: dark brown (7.5YR 4/4) silt loam; strong, coarse prismatic structure; thick, continuous, grayish-brown (10YR 5/2) clay films coating peds and lining channels; light brownish-gray (10YR 6/2) seams occupying 15 percent of the volume; polygons ranging from 5 to 20 cm wide; gradual, wavy boundary.
Btx2	75 cm+: dark brown (7.5YR 4/4) silt loam; strong, coarse prismatic structure; light brownish-gray (10YR 6/2) seams occupying 5 percent of the volume; polygons ranging from 10 to 30 cm wide.

Severely Eroded Site, Holly Springs, MS (fig. 2d)

Horizon	Description
Ap	0 to 10 cm: yellowish-brown (10YR 5/6) silt loam; weak, fine granular structure; few fine roots; few distinct, pale brown (10YR 6/3) silt coatings dispersed throughout the matrix; common, fine to medium, very dark grayish-brown (10YR 3/2) Fe-Mn nodules; abrupt, smooth boundary.
Bx1	10 to 43 cm: dark brown (7.5YR 4/4) silt loam; strong, coarse prismatic structure; thick, continuous grayish-brown (10YR 5/2) clay films throughout; light brownish-gray (10YR 6/2) seams ranging from 1 to 16 cm wide and occupying 35 to 40 percent of the volume; polygons badly degraded, ranging up to 10 cm; common, fine to medium, dark grayish-brown (10YR 3/2) Fe-Mn stains on prism faces; gradual, wavy boundary.
Bx2	43 cm+: dark brown (7.5YR 4/4) silt loam; strong, coarse prismatic structure; light brownish-gray (10YR 6/2) seams ranging from 1 to 10 cm and occupying 15 to 20 percent of the volume; polygons ranging up to 30 cm wide; common, fine to medium, dark grayish-brown (10YR 3/2) Fe-Mn stains on prism faces.

Selected physical and chemical data for these profiles appear in table 1. The differences found in the physical properties among the profiles were consistent for soils eroded to different depths. Most of the changes in chemical properties, however, could not be accurately compared between uneroded and eroded sites because the eroded sites have been chemically amended. The primary properties that indicate modification due to accelerated erosion include (1) a decrease in the thickness of A horizon and in organic matter content; (2) a progressive lightening of color at the surface with increased erosion; (3) a substantial increase in the bulk

density of the plow layer, compared with the uneroded A horizon; and (4) a gradual increase in sand and clay accompanied by a decrease in silt. In most instances the values recorded for these properties in the eroded profiles were also found in uneroded profile samples, but only from well within the B horizon. This fact indicates that the properties observed in the Ap horizons of the eroded profiles are the direct result of topsoil removal by erosion and subsequent inclusion of lower horizons (for example, E, Bw, and Bt) into the Ap horizon.

The relationship between soil properties and depth to fragipan was revealed in more detail by separate analysis of 30 individual samples collected at random from the plow layer (0 to 15 cm) of experimental plots. These areas comprised 0.04 ha immediately adjacent to the four pedons. The analyses were conducted to apply the relationships to field-scale situations. The plots at all sites were grouped on the basis of relatively similar depths to the fragipan. The average depth to fragipan was regressed against average values for characterization parameters to establish statistical relationships.

As mentioned, a decreasing depth to fragipan resulted in significant increases in sand and clay and a decrease in silt content (table 2). These changes were the result of a combination of factors, including preferential removal of the high-silt surface horizon, gradual incorporation of clay-rich B horizon materials into the surface horizon by cultivation as profile thickness decreased, and accumulation of sand-sized Fe-Mn nodules at the surface as the smaller, less stable soil aggregates were disrupted and removed by erosion. The value and chroma components of soil color increased as depth to fragipan increased. This indicates that the surface horizons became progressively lighter as the organic matter content decreased and as B and E horizon materials were incorporated. Available water content and percentage of aggregation decreased slightly with the decrease in depth to fragipan, whereas, modulus of rupture increased. Bulk density at the eroded sites averaged 1.34, compared with 1.03 Mg/m^3 at the uneroded site. These changes are attributed to a decline in organic matter levels and an increase in clay content of the A horizon.

Several chemical properties (such as pH, cation exchange capacity, and exchangeable Mg, A1, K, and H) were poorly related to depth to fragipan because of past lime and fertilizer amendments at the cultivated sites (table 3). A noticeable difference among the sites was the relatively high pH and greater concentrations of Ca, Mg, and K at the uneroded site, even though it had never been amended. An explanation may be that trees recycled bases from the subsoil at the uneroded site and that this recycling eventually resulted in an accumulation of basic cations in the A1 horizon following leaf fall. The changes in chemical properties assumed to be unaffected by past amendments (Na, Fe, Mn, and organic matter) were more closely related to depth to fragipan. The increase in exchangeable Na along with an increase in severity of erosion suggests that subsurface horizons with greater Na concentrations were gradually exposed (table 1). The decrease in organic matter indicates that the original A horizon was removed. Increases in extractable Fe with decreases in depth to fragipan are attributed to increases in clay and Fe-Mn nodules in surface horizons as erosion progresses. The large decrease in extractable Mn associated with decreasing depth to fragipan is believed to be directly related to trends in organic matter that can act as a complexing agent for this element.

Erodibility of Fragipan Soils

Soil erosion losses from the loess soils in the lower Mississippi River Valley are among the highest in the United States, with estimated average losses ranging from 34 to over 56 Mg/ha/yr (Langdale et al. 1985). Such erosion problems originate because the loess soils have inherent properties that make them susceptible to erosion. Specifically, they have a homogeneous particle size distribution that is about 80 percent silt. Further, the predominant fragipan soils within the region fall in the fine-silty particle size class, which has a relatively low clay content and is essentially devoid of sand. The low clay content, coupled with low organic matter concentrations after cultivation, creates unstable soil aggregates. Rainfall quickly destroys most aggregation in the surface layer, which seals, leading to low saturated hydraulic conductivity and greater runoff and erosion than in better aggregated soils.

In addition, the region receives abundant rainfall, with mean annual precipitation ranging from about 122 cm in the north to 163 cm in the south. Much of it occurs in the form of intense rainstorms, with energies ranging up to 850 N/ha (Langdale et al. 1985). Another contribution is sloping topography. Fragipan soils can be found on landscapes with slopes exceeding 25 percent; however, much gentler slopes are the norm.

One would suspect there would be differences in erodibility between soil series in the loess uplands when clay and iron oxide contents differ, such as those that exist between some fragipan and nonfragipan soils. No research has yet been designed to determine the erodibility of fragipan soils in relation to other silt loam soils without fragipans in this loess upland region. Erodibility studies have shown silt loam soils to be more erodible than other soil types (Meyer and Harmon 1984). Within the silt loam grouping, the two primary fragipan soils of the region, Grenada and Loring, ranked near the bottom in terms of soil loss, at 58 and 48 Mg/ha, respectively. The lower susceptibility of these two soils is unclear, unless differences in profile thickness were a factor.

Soil loss and runoff from Grenada can vary (fig. 3) depending on the depth of past erosion (Rhoton et al. 1990). Total soil loss from an uneroded site following a sequence of dry and wet runs was 31 Mg/ha. A slightly eroded site yielded 80 Mg/ha, compared with 71 and 59 Mg/ha at moderately and severely eroded sites, respectively. The differences are primarily attributed to changes in organic matter and clay

contents as depth of erosion became progressively worse. The large increase in soil loss between the uneroded and slightly eroded sites may be explained by a 71-percent decrease in organic matter (table 1), which reduced aggregate stability from 94.3 to 87.1 pereent. The progressive decrease in soil loss among the slightly, moderately, and severely eroded sites was attributed to an increase in clay content from 15.5 to 17.9 and then to 19.2 percent.

Another factor that probably contributed to the decline in soil loss was an increase in Fe-Mn nodule concentrations on the surface of the more deeply eroded sites (Rhoton et al. 1991). These materials are more stable than soil aggregates of similar size and therefore are not broken down as easily by the impact of raindrops and removed by runoff. Consequently, less soil loss was measured at sites having higher concentrations of Fe-Mn nodules.

Relationship of Productivity to Erosion

In terms of plant production, no individual property is more important than the ability of fragipan horizons to restrict the depth of plant root penetration and water movement. This adverse characteristic creates a fragile soil system where continued erosion of the surface soil has a progressively greater impact on productivity, because plant roots must essentially depend on the water and nutrients stored in the soil above the fragipan. Therefore, the productivity of these fragipan soils varies considerably, depending on the extent of past erosion.

Although erosion can seriously affect soil fertility through the removal of nutrients, most of these problems can be solved by the chemical amendments. The loss of soil-water storage capacity as profile thickness decreases is a far more serious problem that cannot be easily ameliorated.

Soybean yields are determined primarily by rainfall amounts (soil-water content) during the flowering and pod-filling stages. In a 3-yr study of erosion and productivity, the reproductive stage largely coincided with the last wk of July through August each yr (Rhoton 1990). Total rainfall recorded for the growing season increased from 1984 through 1986; however, the portion that fell during the reproductive stage increased from 1984 to 1985, and then decreased in 1986 to levels below the 1984 readings (table 4). Soil-water content during the pod-filling stage was greatest in 1985 and least in 1986 (table 5). The differences in soil-water content among the three sites reflect relative soil thickness above the fragipan. During the course of this study, the slightly eroded site (59 cm) stored an average of 30 percent more water than the moderately eroded area (43 cm) and 72 percent more water than the severely eroded (20 cm) area. The moderately eroded area stored approximately 58 percent more water than the severely eroded area.

The differences in soil-water content resulted in grain and biomass yields that varied with soil depth above the fragipan and with growing season (table 6). The largest grain yields were measured in 1984 and the least in 1986. The moderately eroded site was an exception; its largest yield occurred in 1985. In 1984 and 1985, the average difference in grain yield between the slightly eroded and severely eroded plot was 441 kg/ha. In 1986, this difference was 737 kg/ha.

With the exception of 1984, grain yields corresponded directly to average depth to fragipan. Yields for the slightly eroded site exceeded those of the moderately eroded site, which exceeded those of the severely eroded site. In 1984, the severely eroded plots produced greater yields than the moderately eroded plots because of rainfall distribution during the vegetative and reproductive growth stages. Approximately 68 percent of the total rainfall in the 1984 growing season occurred during the reproductive stage, and 41 percent of this amount fell in one event—64 mm on August 27. Therefore, plants grown on the severely eroded plots had access to more water, because the shallow fragipan prevented the water from infiltrating as far below the plant root zone as it had in the deeper plots.

The decrease in grain yields from 1984 to 1985, despite higher rainfall and soil-water content at all depths, is attributed to higher temperatures (an increase of 4.4 °C) during the pod-filling stage (Thompson 1970). Another important consideration is lower rainfall during late pod filling, since the 1984 rainfall pattern during this period was not repeated in succeeding yr. When the patterns for all 3 yr were compared, grain yields decreased substantially in 1986 compared with 1984 and 1985, with the exception of the slightly eroded site. These relatively low yields are attributed to increased water stress from insufficient August rainfall, especially during the second half of the month. Rainfall during this period was 2.5 cm in 1986, compared with 9.2 and 7.6 cm in 1984 and 1985, respectively.

Biomass yields appeared to be more sensitive to rainfall amounts and distribution than grain yields (table 6). Maximum vegetative yields usually occur when rainfall is greatest before pod filling. Since grain is a component of biomass, however, rainfall distribution throughout the growing season must also be considered. Thus, biomass yields should be greatest when rainfall is evenly distributed between the vegetative and reproductive stages. Generally, biomass yields were greatest in 1985, followed by 1984 and 1986. Rainfall during the vegetative stage was 49 percent of the total in 1985, 32 percent in 1984, and 74 percent in 1986 (table 4). As the rainfall over the three sites approached a distribution of 50 percent in the vegetative and reproductive stages, biomass yields showed a smaller range. As the rainfall distribution deviated from 50 percent, the yields decreased disproportionately on the shallower plots.

The value to grain yields of soil depth above the fragipan was determined on an incremental basis using yields from groups of plots with similar depths. Average depth within a group was plotted against average yield for that group for the 3-yr study, and a curve was then fitted to these points (fig. 4). Approximate yield losses per cm of soil loss above the fragipan were calculated from a soil depth of 60 to 20 cm in 10-cm increments. The greatest yield loss (240 kg/ha)

occurred as soil depth decreased from 60 to 50 cm. In the 50- to 40-cm range, 170 kg/ha were lost. Yield losses between 40 and 20 cm were relatively constant at 60-70 kg/ha. The yields appeared to begin a sharp decline below the 20-cm depth, an expected development as the plow layer approached the fragipan surface.

Management of Fragipan Soils

Research indicates that the response of fragipan soils to different management practices is similar to that of other loess-derived soils which contain no fragipan horizon. A possible exception may be shallow soils where the original A horizon and portions of the B horizons were lost to erosion. In these cases, fragipan horizons generally exert a greater influence on the productivity of soil, by limiting plant root accessibility to water and nutrients stored above the fragipan. Also, the fertility of the plant growth medium deteriorates, since the Fe oxides in Fe-Mn nodules can fix substantial amounts of phosphorus in a form unavailable to the plant. As the depth of erosion increases, so does the concentration of these nodules in the plow layer.

Conservation tillage has shown promise as a management system in studies conducted on fragipan soils. Some research showed that after 2-yr no-till cotton produced substantially greater yields than that farmed with conventional treatments on moderately deep fragipan soils (Dabney et al. 1993a). Similar results were observed between treatments for soybeans, where no-till produced a 5-yr average of 314 kg/ha more than conventional treatments. In this same study, no-till reduced runoff by 50 percent and soil loss was 6 times less than conventionally tilled treatments (Dabney et al. 1993b).

Some form of reduced tillage is of absolute necessity on these soils even if the yields do not exceed those from conventional tillage. Otherwise, crop yields will progressively decrease with topsoil loss, notwithstanding damages created off-site by sediment.

In addition to retarding soil losses, a beneficial aspect of reduced tillage systems on shallow fragipan soils is water conservation. As previously mentioned, no-till can reduce runoff by 50 percent on these soils. Such a reduction makes more soil water available for plant growth, especially on shallow sites where fragipan horizons limit the depth of water movement within the primary rooting zone. Increased soil-water availability could mean the difference between profit and loss for some crops if rainfall is inadequate during critical plant reproductive stages.

Future Research Needs

Vast areas of fragipan soils have formed in highly erodible loess. The natural processes responsible for the generation of loess-derived soils are no longer active. Thus, no more soil is forming of the quality being lost to erosion. Reclamation of severely eroded fragipan soils is generally considered economically impractical. In instances of severe erosion, irrigation is not an option because water-storage capacity is too limited. Runoff from slopes becomes an additional problem. Plowing into fragipan horizons to increase profile thickness is practically impossible. Once exposed at the surface, fragipan horizon materials are much more erodible than overlying horizons. Management systems should be developed that maintain these soils in a productive state. The best systems would be the result of research that utilizes different scientific disciplines and a comprehensive systems approach.

Initially, researchers must develop some understanding of how fragipan soils form. At a minimum, the research should identify major processes and their influence on soil behavior and land use and indicate common attributes among fragipan soils. Given the wide distribution of these soils and their importance to the agricultural economy, this research should be assigned priority status.

This genesis-morphology information could serve as a basis for designing studies of applied management, erosion, and productivity. Long-term conservation tillage studies are needed on a range of depths to fragipan. Aside from evaluating the influence of reduced tillage on yields and reducing erosion on relatively shallow systems, this research would help identify depths to fragipan that cannot be row-cropped regardless of management system and that should be taken out of production. Water balances and carbon cycling should be carefully monitored, since they may influence increased degradation of the fragipan surface and depth of root growth. Fertilizer-use efficiencies should be determined, particularly where Fe-Mn nodule accumulations are evident in surface horizons, since these materials are scavengers of fertilizer-applied phosphorus.

The erodibility of fragipan soils should be evaluated in watersheds where soil loss can be monitored. In such situations, pedological parameters known to influence erodibility should be delineated and quantified at different landscape positions, and the zones should be weighted to determine their relative contribution to total soil loss. This information could be used to determine if different management systems are needed at different landscape positions to effect maximum reduction in soil losses. Within a watershed, water movement through fragipan soil profiles needs to be monitored to determine how much lateral flow along fragipan surfaces eventually leaves the watershed in surface waters. Such efforts, in conjunction with studies of fragipan micromorphology that trace water movement, may identify patterns of pesticide movement.

Field and laboratory research is also needed to develop amendment systems that increase fragipan surface degradation beyond that which occurs naturally. A range of amendments should be evaluated, including wastes from industrial, municipal, and farm sources. If an increase in rooting depths can be achieved, improved crop yields should result. Amendment systems, when used in conjunction with conservation tillage practices, would ensure the indefinite maintenance of a highly productive soil base.

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Table 1. Selected physical and chemical properties of uneroded and eroded pedons

Horizon	Depth (cm)	Color (moist)	Sand	Silt	Clay	Bulk density (Mg/m^3)	pH (H_2O)	Exchangeable Ca	Mg	K	Na	Acidity	Al	H	Effective CEC*	BS†	Extractable Fe	Mn	Organic matter
			------%	------	------			------(cmol/kg)							------	(%)	--(mg/kg)--		(g/kg)
Virgin (uneroded)																			
A1	0-10	10YR3/2	0.5	82.1	17.4	1.08	6.5	8.4	3.1	0.5	0.02	0.1	0.1	0.0	12.1	99	2.8	287.0	49.8
A2	10-20	10YR3/3	0.4	82.7	16.9	1.08	5.3	1.3	1.6	0.3	0.01	1.4	1.2	0.2	4.6	70	37.0	259.0	13.7
BA	20-36	10YR4/4	2.6	79.3	18.1	1.28	5.1	1.4	2.4	0.3	0.02	1.6	1.4	0.2	5.7	72	58.4	191.0	7.3
Bw	36-48	10YR5/6	3.1	78.0	18.9	1.44	5.0	1.6	3.3	0.3	0.02	2.6	2.3	0.3	7.8	67	60.9	146.0	4.4
Bt	48-64	10YR5/6	3.6	75.8	20.6	1.51	4.7	1.2	3.1	0.2	0.04	4.7	4.3	0.4	9.2	49	66.4	51.9	2.7
E/Btx	64-74	10YR6/2	3.5	74.8	21.7	1.54	4.6	1.2	3.7	0.2	0.06	6.2	5.6	0.6	11.4	46	63.5	34.8	2.1
Btx1	74-127	7.5YR4/4	2.7	71.1	26.2	1.58	4.4	1.9	5.6	0.2	0.18	7.4	6.7	0.7	15.3	52	92.0	47.2	1.5
Btx2	127+	7.5YR4/4	1.2	77.9	20.9	1.60	4.7	3.2	7.5	0.2	0.62	2.3	1.6	0.7	13.8	83	60.2	34.6	1.0
Slightly eroded																			
Ap	0-15	10YR4/4	3.9	78.4	17.7	1.48	6.6	5.7	0.8	0.3	0.04	0.1	0.0	0.1	6.9	99	30.4	213.0	14.5
BA	15-28	10YR5/6	1.5	71.7	26.8	1.46	5.8	4.3	1.8	0.2	0.07	0.7	0.6	0.1	7.1	90	54.7	78.8	4.1
Bt1	28-43	10YR5/6	1.8	73.1	25.1	1.37	5.1	2.9	2.6	0.2	0.08	1.8	1.6	0.2	7.6	76	74.4	99.0	2.8
Bt2	43-61	10YR5/4	2.2	76.4	21.4	1.41	4.9	1.5	2.3	0.2	0.09	3.0	2.7	0.3	7.1	58	76.7	79.5	2.0
E/Bx	61-74	10YR6/2	2.1	80.5	17.4	1.49	4.9	0.8	2.2	0.2	0.11	3.3	2.9	0.4	6.6	50	67.7	22.9	1.0
Btx1	74-88	7.5YR4/4	2.3	73.8	23.9	1.52	5.1	1.1	4.5	0.2	0.32	4.0	3.3	0.7	10.0	61	77.9	16.2	0.8
Btx2	88-100+	7.5YR4/4	4.2	74.6	21.2	1.60	5.2	0.7	4.7	0.2	0.60	3.7	3.4	0.3	9.9	63	66.7	11.7	0.7
Moderately eroded																			
Ap	0-11	10YR4/4	3.1	78.2	18.7	1.43	6.4	5.8	0.8	0.4	0.03	0.0	0.0	0.0	7.0	100	34.2	205.0	12.4
Bw1	11-23	10YR5/6	2.5	75.7	21.8	1.46	4.9	3.3	1.3	0.2	0.05	2.5	2.1	0.4	7.4	64	74.4	100.0	2.7
Bw2	23-37	10YR6/4	2.3	78.0	19.7	1.41	4.7	1.9	1.8	0.2	0.09	3.4	3.0	0.4	7.4	54	81.3	86.1	1.6
E/Bx	37-47	10YR6/3	2.4	81.0	16.6	1.51	4.8	1.1	2.4	0.1	0.10	3.3	2.9	0.4	7.0	53	62.6	23.6	0.9
Btx1	47-75	7.5YR4/4	2.5	73.2	24.3	1.55	4.9	1.2	4.4	0.2	0.31	4.6	3.9	0.7	10.7	57	73.1	12.5	0.8
Btx2	75-100+	7.5YR4/4	4.8	73.6	21.6	1.58	5.3	1.4	4.9	0.1	0.53	2.4	1.8	0.6	9.3	74	59.8	31.7	0.1
Severely eroded																			
Ap	0-10	10YR5/6	4.7	74.4	20.9	1.44	5.4	3.9	2.8	0.2	0.07	0.4	0.2	0.1	7.4	95	61.8	128.0	10.1
Bx1	10-43	7.5YR4/4	2.0	74.3	23.7	1.54	4.9	1.9	5.2	0.2	0.26	2.9	2.4	0.5	10.5	72	74.3	23.5	1.1
Bx2	43-48+	7.5YR4/4	5.6	74.1	20.4	1.58	5.0	1.9	7.1	0.2	0.54	2.9	2.3	0.6	12.6	77	48.2	6.4	1.4

* CEC = cation-exchange capacity.

† BS = base saturation.

Table 2. Relationships between soil physical properties at the 0- to 15-cm sampling depth as a function of depth to fragipan

Soil property	Average depth to fragipan (cm)								Regression equation (n = 8)	r^2
	16	24	37	46	56	65	92	106		
Sand (%)	4.8	5.5	3.4	3.3	3.6	3.7	0.3	0.4	Y = 6.157-0.0551X	0.893‡
Clay (%)	20.8	18.9	18.9	19.3	17.5	16.1	16.3	16.3	Y = 20.653-0.0478X	0.771†
Silt (%)	74.4	75.6	77.6	77.4	78.8	80.2	83.4	83.3	Y = 73.188+ 0.1030X	0.972‡
Color value (%)	3.98	3.87	3.72	3.73	3.53	3.48	2.58	2.60	Y = 4.358-0.0166X	0.927‡
Color chroma (%)	3.93	3.99	4.03	4.11	3.73	3.60	2.11	2.60	Y = 4.759-0.0235X	0.808†
Available water content (kg/kg)	0.16	0.16	0.18	0.18	0.17	0.18	0.18	0.19	Y = 0.161+0.0231X	0.585*
Modulus of rupture (kPa)	50.0	50.4	50.3	47.4	34.0	27.5	9.5	7.3	Y = 65.121-5.5553X	0.931‡
Aggregation (%)	87.5	89.0	90.2	89.9	88.0	87.2	94.1	94.4	Y = 86.297+0.0679X	0.576*

* = Significant at the 0.05 level.
† = Significant at the 0.01 level.
‡ = Significant at the 0.001 level.

Table 3. Relationships between soil chemical properties at the 0- to 15-cm sampling depth as a function of depth to fragipan

Soil property	Average depth to fragipan (cm)								Regression equation (n = 8)	r^2
	16	24	37	46	56	65	92	106		
pH	5.4	5.6	6.1	5.9	6.6	6.7	6.2	6.1	Y = 5.655+0.0079X	0.324
Exchangeable Ca (cmol/kg)	4.6	4.9	6.4	6.4	6.7	6.6	8.9	8.2	Y = 4.162+0.0438X	0.897
Exchangeable Mg (cmol/kg)	2.6	1.7	1.0	1.0	0.9	0.7	2.5	2.3	Y = 1.306+0.0050X	0.042
Exchangeable K (cmol/kg)	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.3	Y = 0.108+0.0021X	0.679*
Exchangeable Na (cmol/kg)	0.13	0.11	0.05	0.04	0.04	0.04	0.00	0.00	Y = 0.129-0.0013X	0.879‡
Exchangeable Al (cmol/kg)	1.08	0.74	0.14	0.18	0.06	0.06	0.07	0.06	Y = 0.801-0.0091X	0.543*
Exchangeable H (cmol/kg)	0.30	0.23	0.11	0.15	0.05	0.02	0.05	0.05	Y = 0.262-0.0025X	0.634*
Cation-exchange capacity (cmol/kg)	8.8	7.8	7.9	8.0	7.9	7.6	11.9	11.0	Y = 6.772+0.0379X	0.533*
Extractable Fe (mg/kg)	53.2	48.2	39.9	43.8	36.3	33.5	11.9	11.8	Y = 61.172-0.4788X	0.952‡
Extractable Mn (mg/kg)	124.7	148.7	194.3	188.8	256.3	305.1	616.6	650.0	Y = -36.195+6.2998X	0.924‡
Organic matter (g/kg)	6.8	7.2	11.0	11.0	12.7	14.1	53.1	50.0	Y = -0.956+0.0551X	0.823†

* Significant at the 0.05 level.
† Significant at the 0.01 level.
‡ Significant at the 0.001 level.

Table 4. Rainfall recorded during the soybean pod-filling stage for crop years 1984-1986

	Rainfall amounts (mm)		
Recording dates	1984	1985	1986
July 25-31	33	79	2
August 1-7	20	28	25
August 8-14	13	0	56
August 15-21	28	48	10
August 22-28	64	28	15
August 29-31	0	0	0
Total during pod-fill	158	183	108
Total for growing season	231	358	419

Table 5. Average water content in the profile above the fragipan at the three differentially eroded sites during the soybean pod-filling stage (July 25-August 31)

Site	Average plot depth (cm)	Sampling depth (cm)	Soil-water content* (cm) 1984	1985	1986
Slightly eroded	59	0-7.5	1.5	1.9	1.0
		7.5-30.5	5.3	5.5	3.8
		30.5-59.0	6.7	7.4	5.2
Total			13.5	14.8	10.0
Moderately eroded	43	0-7.5	1.4	1.9	1.0
		7.5-30.5	4.7	5.4	3.9
		30.5-43.0	2.9	3.2	2.4
Total			9.0	10.5	7.3
Severely eroded	20	0-7.5	1.3	1.8	0.9
		7.5-20.0	2.2	3.4	1.5
Total			3.5	5.2	2.4

* These values were determined by multiplying volumetric water content times thickness of the sampling depths.

Table 6. Soybean grain and biomass yields recorded at the eroded sites

Year/site	Average plot depth (cm)	Grain yields (kg/ha)	Biomass yields (kg/ha)
1984			
Slightly eroded	59	2,622	7,985
Moderately eroded	43	2,032	7,486
Severely eroded	20	2,181	6,740
1985			
Slightly eroded	59	2,343	7,967
Moderately eroded	43	2,055	7,727
Severely eroded	20	1,902	7,026
1986			
Slightly eroded	59	2,286	6,810
Moderately eroded	43	1,773	5,532
Severely eroded	20	1,549	5,217

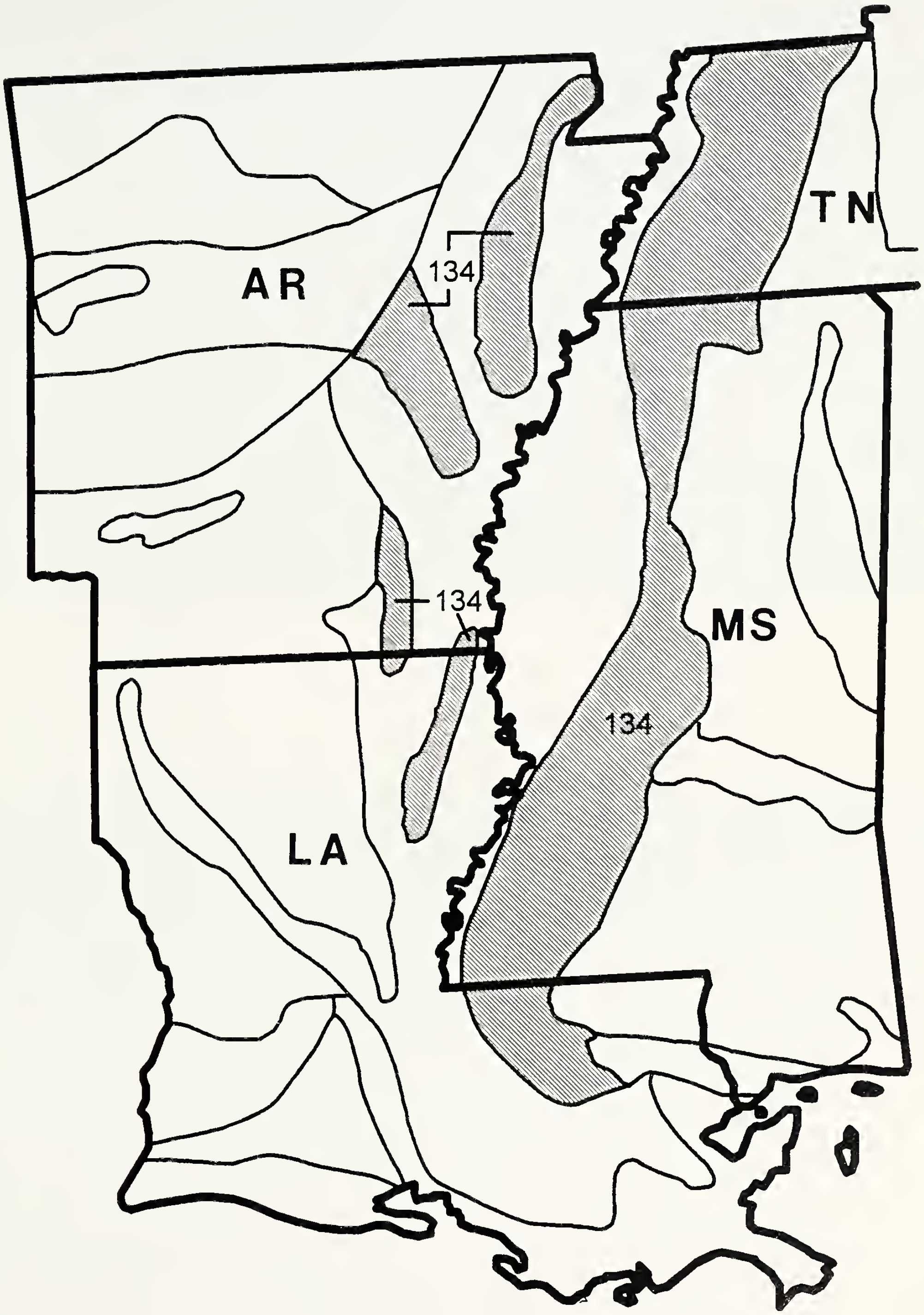

Figure 1. Location of Major Land Resource Area 134 in the lower Mississippi River Valley

Figure 2. Soil Profiles. *A*, an uneroded fragipan soil pedon, Crockett Co., TN. *B*, a slightly eroded fragipan soil pedon, Holly Springs, MS.

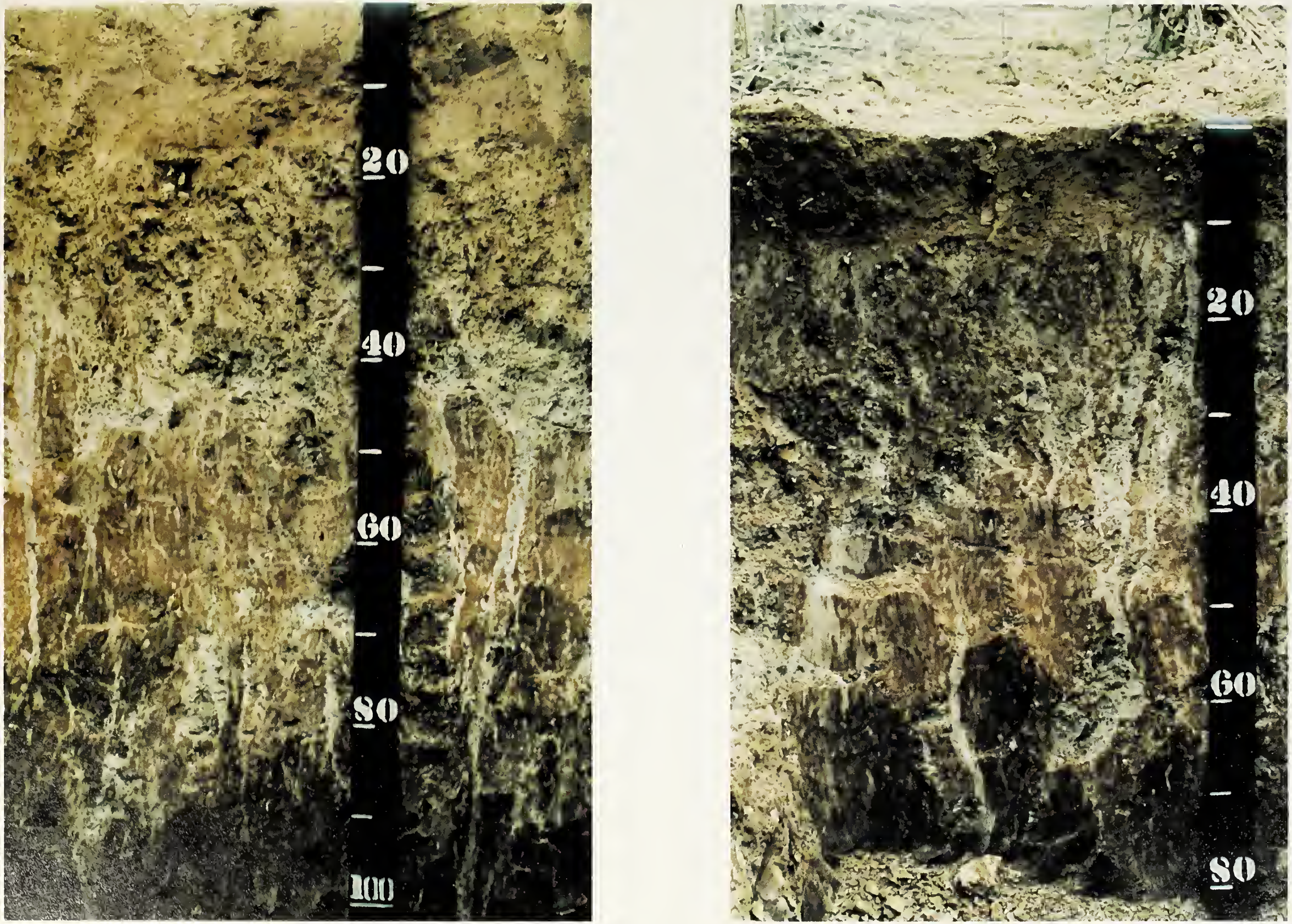

Figure 2. Continued—Soil Profiles. *C*, a moderately eroded fragipan soil pedon, Holly Springs, MS. *D*, a severely eroded fragipan soil pedon, Holly Springs, MS.

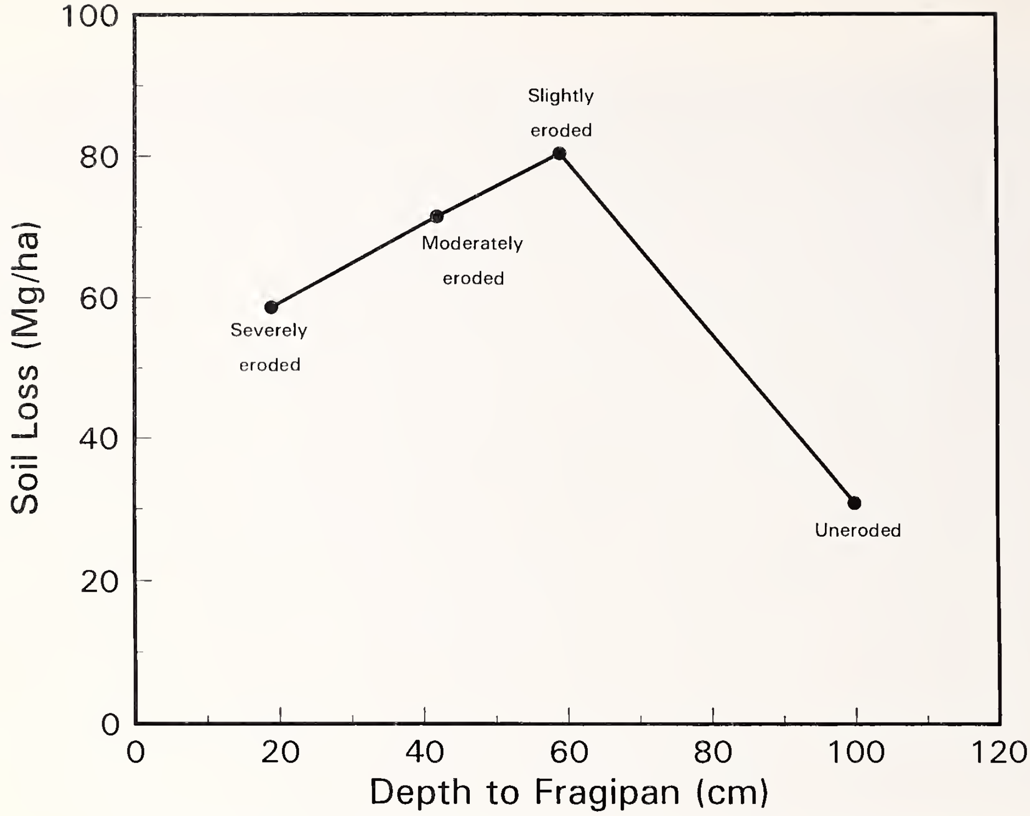

Figure 3. Soil loss measured in runoff from rainfall simulator plots as a function of depth to fragipan

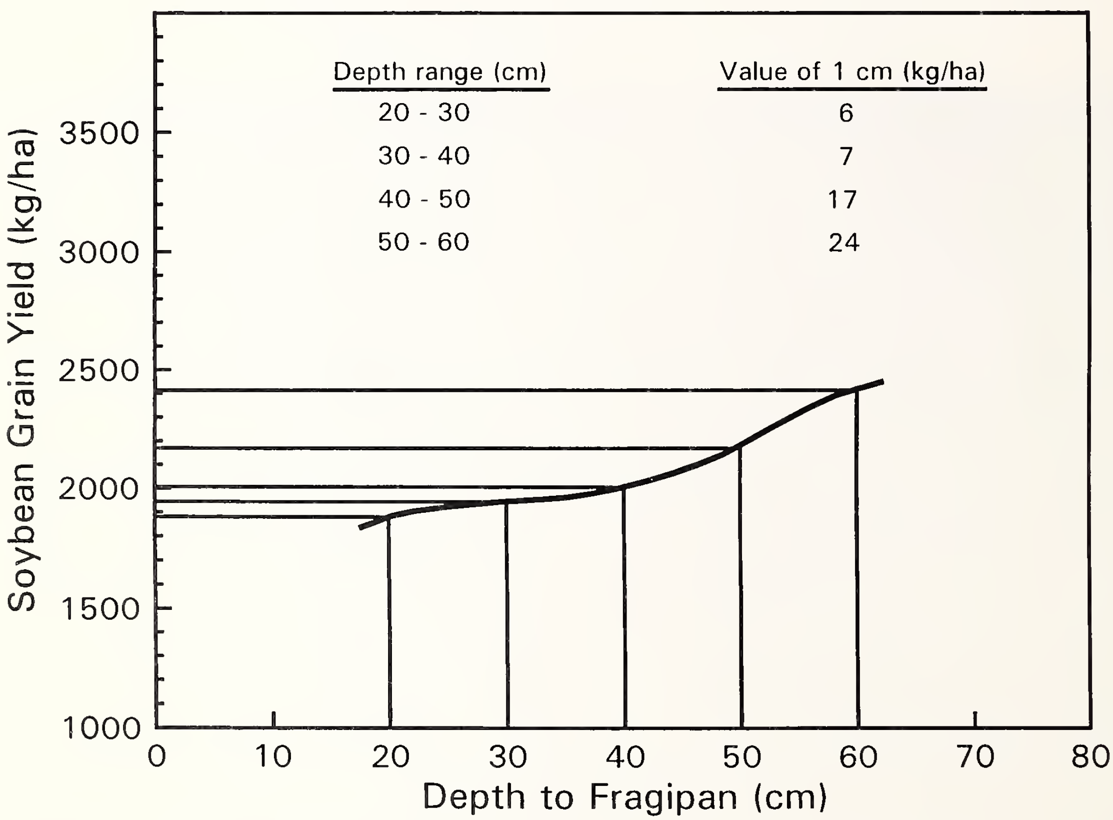

Figure 4. Approximate soybean grain yield loss that results from the loss of soil above the fragipan